

Analysis of Sliding Wear Rate Variation with Nominal Contact Pressure*

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Abstract:

The variation of wear rate with nominal contact pressure during sliding wear tests in ball-on-flat geometry for two sliding systems was analyzed. Using interrupted wear test data a functional relationship is established between the “instantaneous” wear rate and the nominal contact pressure for M-10 steel (data from literature) and TZP-ZrO₂ materials. The wear rates and the contact pressures were connected by simple wear models that exhibited a variation in wear mechanism. The results show how it is possible to use a simple curve-fitting program to examine the plausibility of various wear models. In M-10 steel, the transition in wear fits very well to a frictional heating model that produces surface softening. In ZrO₂, stress-induced tetragonal to monoclinic phase transformation is a candidate for the wear mechanism transition.

Introduction

When two surfaces are in loaded sliding contact, stresses are imposed on both solids as a result of normal and tangential forces that arise from sliding. Frictional heat is also generated at

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the sliding-contact interface. The imposed stresses and frictional heating at the contact interface are the key driving forces for the occurrence of wear at a sliding-contact interface. Consequently, the wear rates and wear mechanisms are determined in large part by the magnitude of these driving forces.

The forces and temperature rise are determined by the contact pressure, the sliding speed, and the friction coefficient. In many wear tests, the friction coefficient is continuously measured, while the sliding speed and the load are held constant. However, simple benchtop wear tests are often conducted with a nonconformal-contact configuration, such as ball-on-flat, cylinder-on-flat, or cylinder-on-cylinder [1] due to their ease of alignment of test specimens and the elimination of edge loading at the contact during testing.

If one assumes an elastic contact, the initial contact pressure can be calculated using Hertzian theory. In many reports, only this initial Hertzian contact pressure may be specified, but during the test, the nominal contact pressure drops very rapidly. In a point-contact geometry, several orders of magnitude decrease in the contact pressure can occur during wear. Such a drop in pressure will produce large variations in contact stress and frictional heating, producing changes in the wear mechanisms, and variation in the wear rate.

A common practice is to report an overall wear rate, which is less than the full amount of information potentially obtainable during the course of a test. If the wear scar dimension as a function of time is measured, both the nominal contact pressure and the wear rates can be calculated as a function of time (or distance). A relationship can then be established between the nominal contact pressure and the wear rate. Such an analysis provides a connection between the wear rate and the driving force for wear, and can help elucidate the mechanisms of wear. The ability to assess the variation of wear rates and wear mechanisms during the course of a single test can help discern trends when conducting multiple tests at differing loads to evaluate the effect of contact stress on wear, e.g., Ref. 2.

Except in the catastrophic case of scuffing, wear generally occurs at the contacting surfaces. The analysis presented in this paper attempts to correlate measured macroscopic wear

rates with macroscopic-level nominal contact pressure. The main objective of this paper is to assess, for two very different sliding systems, the variation of contact pressure as well as the wear rates in the nonconformal-contact wear tests. Variation in wear rates may indicate the presence or absence of wear transitions.

Average Wear Rate and Instantaneous Wear Rate

When wear data are reported, the overall "wear rate" R during sliding is often calculated by dividing the total measured wear volume V_T at the end of test by the total sliding distance (or time duration) of the test X_T , i.e., $R = \frac{V_T}{X_T}$. This approach assumes that wear rates are constant and wear mechanisms are unchanging during the course of the test, and that the average wear rate is characteristic of the entire test.

If one develops simple physically intuitive expressions for wear rate, in which wear rate is expressed in terms of test parameters (e.g., speed, temperature, load) then a comparison with measured data requires either the model be integrated and fitted to a graph of V vs. P , or the expression be fit to $\frac{dV}{dx}$ vs. P . Often the latter is the desired approach because integration is difficult.

For wear tests with interrupted measurements, such as those by Mecklenburg [3], the instantaneous wear rate can be approximated by measuring the amount of wear that occurs between intervals n and $n+1$, divided by the sliding distance (or time for constant speed) over which it occurs $\left. \frac{dV}{dx} \right|_n \approx \frac{\Delta V}{\Delta x} = \frac{V_{n+1} - V_n}{X_{n+1} - X_n}$. The instantaneous wear rate may vary during the course of the test.

This paper focuses on the ball-on-disk geometry, which is often used because of its sensitivity and ease of detecting even small amounts of wear. When a ball, or hemispherical cap, slides against a flat, a circular wear scar is produced on the ball. The volume V of the material worn from the ball is $V = \frac{\pi r^4}{4 R_b}$, where r is the wear scar radius on the ball, and R_b is the radius of the ball. The macroscopic contact pressure is L/A , where L is the load in force units, and A is the area of the wear scar. When the test is first started, no wear scar is present, and the initial

contact pressure is L/A_h , where A_h is the contact area calculated using Hertzian theory. The moment that wear occurs, a scar forms, and the pressure plummets rapidly, often by orders of magnitude.

Effective Pressure

Within any interval, the higher instantaneous wear rate can occur nearer to P_i or to P_f , depending on the sliding system. In fact, the M-10 and PSZ systems were specifically used because they have exactly opposite behavior in this respect. If the intervals are sufficiently small, then the differences between P_i and P_f need not be great.

It is not immediately obvious what the time-average effective pressure, P_{eff} , is within the interval as the scar forms and the pressure decreases. P_{eff} could simply be the average of P_i and P_f , which would hold true for some contact geometries. For a ball-on-flat geometry, the volume is proportional to the scar diameter raised to the fourth power, and a greater amount of time is spent within the interval when the pressure in the contact is nearer to P_f than to P_i (assuming reasonably small intervals). This is because wear that occurs at the beginning of an interval causes the scar to increase very rapidly and the pressure to quickly drop, with the decrease lessening due to the square root dependence of pressure on worn volume,

If the instantaneous wear rate $\frac{dV}{dx}$ does not vary too quickly as a function of pressure within an interval, one can make at least a reasonable choice for P_{eff} .

$$P_{eff} = \frac{1}{(x_f - x_i)} \int_{x_i}^{x_f} P(x) dx,$$

If the interval is small then the wear rate is reasonably constant and can be approximated as a

constant S to get $V = S x$. So $P = \frac{L}{\sqrt{S x 4\pi R_b}}$ and $P_{eff} = \frac{1}{(x_f - x_i)} \int_{x_i}^{x_f} \frac{L dx}{\sqrt{S x 4\pi R_b}}$. This gives $P_{eff} = \frac{1}{\sqrt{x_f} + \sqrt{x_i}} \frac{2L}{\sqrt{S 4\pi R_b}}$. Substituting $\sqrt{x} = \frac{L}{P\sqrt{S 4\pi R_b}}$, one finds that $P_{eff} = \frac{2 P_i P_f}{P_i + P_f}$. For example, if $P_i = 20$ and $P_f = 10$, $P_{eff} = 13.3$. For other contact geometries (e.g., cylinder on flat) the expression would be different.

Analysis of M-10 Steel Wear

As a starting point, some ball-on-flat data from the literature were used in which a flat disk was slid against a spherical ball with constant load and speed [3]. The tests were conducted with 3.18-mm (1/8 in.)-diameter balls and 101.6-mm-diameter, 25.4-mm-thick discs, all made from hardened (52 Rc) M-10 steel. The surface roughness was $\sim 1.0 \mu\text{m}$ Ra after burnishing with a thin coating of $(\text{CF}_x)_n$. The sliding speed was held constant at 1.57 m s^{-1} and normal load of 2.2 N. To determine the change in wear scar diameter with time, the test was interrupted after 1, 2, 5, 10, 20, 30, 45, and 60 sec; and 2, 5, 10, 30, 60, 120, and 150 minutes to measure the wear scar diameter.

The data [3] were analyzed to determine dV/dt as a function of P_{eff} by calculating differences in accumulated wear volume, and plotting them against P_{eff} . Figure 1 shows this plot for the M-10 tool steel that was used. In all cases the ball is the wearing specimen.

Clearly, the wear rate varies as a function of pressure. The pressure is high at the start of the test (right side of abscissa), and decreases as wear occurs (left side of abscissa). In order to better understand the behavior, a mathematical relationship between the measured wear rate and the contact pressure was established. Simple curve fitting to of analytical expression to the data was used to examine the goodness of fit.

At low pressures, the wear rate is approximately constant. At higher contact pressures, the wear rate increases by approximately an order of magnitude. The high pressure exists only at the start of the test, and the pressure decreases very rapidly during the few seconds of sliding. The relationship between the wear rate and contact pressure that are chosen must effectively reflect this trend.

When engineering surfaces are brought into sliding contact, asperities will make momentary contact as they slide past each other. Because the real area of contact between asperities is very small when compared with the nominal contact area, a very simple picture would predict the wear rate to be independent of pressure for constant load, because the overall number of contacting asperities does not change, only the distance between them. In addition, for

a wide variety of sliding materials, wear rate is inversely proportional to the hardness of the materials, consistent with a simple picture of asperity shearing.

For this data, one can associate the variation in wear rate with a decrease in hardness, due either to mechanical or thermal stress. Because metals tend to work harden instead of work soften, and the sliding rate is rather high (1.57 m/s) one approach is to associate the increase in wear rate with thermal softening caused by sliding. It will be examined whether this is at all reasonable.

It has been shown that the temperature rise of the surface of a sliding contact is proportional to the nominal contact pressure [4]. The temperature can be expressed as $T = T_a + cP$, where T_a is the ambient temperature (300K), and c is a constant that depends on the thermal diffusivity, the sliding speed, the asperity size, and the friction coefficient which we are forced to assume is constant. If friction data were available then that data could be folded in as well.

The hardness of M-10 steel is known to be relatively constant at low and medium temperatures, with softening occurring at high temperatures [5]. This behavior conveniently expressed in the form

$$H(T) = H_0 \left[1 + \exp\left(\frac{b}{T_s} - \frac{b}{T}\right) \right]^{-1} \quad (\text{modified Fermi function})$$

where T is the contact temperature, T_s is the softening temperature at which the hardness drops to 0.5 of the original value (we take this to be 1000 K from handbooks), and b is a constant that controls the abruptness of the drop. Clearly, this is only approximate, and other functions that exhibit similar behavior could be used. Because it is assumed that the wear rate dV/dx is inversely proportional

to the hardness in this simple model,

$$dV/dx = k \left[1 + \exp\left(\frac{b}{1000K} - \frac{b}{T}\right) \right]^{-1},$$

where k is an overall constant. From inspection of Fig. 1, it is found that k is $3.4 \times 10^{-16} \text{ m}^3/\text{s}$, and if $T = 300K + cP$ is substituted, is possible to fit the resulting expression to the data in Fig. 1 (solid line) with a computer curve-fitting program. (The data from Mecklenburg were specifically reported as a function of time, not distance, and thus the graph is in terms of time. This does not affect the results.) If one does this, the values of c and b are found to be $1.68 \times 10^{-3} \text{ m}^2\text{K}/\text{N}$ and 3724 K, respectively. These numbers can in turn be substituted into the hardness equation to also give Fig.

2, which exhibits the general shape of tool steel hardness. The effect of temperature rise is by not limited to reduction of hardness; other tribological processes that are temperature dependent, for instance oxidation rate will also be affected, and could be modeled similarly. Lim and Ashby attempted to summarize the impact of frictional heating in the construction of their wear mechanism maps [4]. Regardless of the precise mechanism, it is clear that the wear mechanism must involve a process that shows a rapid transition to produce a large change in wear rate.

Analysis of ZrO₂ Wear

There are instances in which the wear rate may decrease instead of increase with larger contact pressure. An example is the wear of yttria- stabilized TZP (tetragonal zirconia polycrystalline). An interrupted pin-on-flat test in reciprocating contact was conducted with a ZrO₂ pin rubbing against a ZrO₂ flat. The hemispherical radius of curvature of the pin was 127 mm. Tests were conducted at a 10 N load and sliding speed of 0.05 m/s. The instantaneous wear rates and P_{eff} were calculated as a function of sliding distance as before (Fig. 3).

Here the wear rate is substantially lower at higher pressures. This behavior has been associated with the stress- and temperature- induced tetragonal-to-monoclinic phase transformation that occurs in the ZrO₂ material [6]. Because of the slow sliding speed (0.05 m/s) it is thought that heating is minimal. The phase transformation is martensitic and occurs suddenly, and is accompanied by an ~ 5% volume increase that leads to compressive residual stress and toughening.

One can change the expression slightly to incorporate stress-induced toughening as the dominant factor affecting wear rate. A semianalytical treatment [7] found that the wear resistance is proportional to the inverse square root of the fracture toughness, or $\frac{dV}{dx} \propto \frac{1}{\sqrt{K}}$. The toughness is low at low pressures and increases abruptly when a martensitic toughening transformation occurs. A simple function for toughness that exhibits a sudden transition is the modified Fermi function, this time cast in the form

$$K = K_o + K_1 / \left[1 + \exp\left(\frac{c}{P} - \frac{c}{P_{0.5}}\right) \right]$$

where a number of constants

are unavoidably present, and $P_{0.5}$ is the pressure at which the toughness is one-half maximum. If the expression for K is substituted into $\frac{dV}{dx}$, above, one obtains

$$\frac{dV}{dx} = 1 / \sqrt{K_o + K_1 / \left[1 + \exp\left(\frac{c}{P} - \frac{c}{P_{0.5}}\right) \right]}$$

The solid line in Fig 3 shows the curve fit of the data to this expression. These numbers can in turn be substituted into the toughness equation to also give Fig. 4 where the best-fit value of $P_{0.5}$ is $\sim 1.8 \times 10^7$ Pa.

Summary

Although the nonconformal-contact configuration is desirable for wear tests, the usual practice of reporting average wear rate over the duration of such tests can be misleading. These tests have shown that contact pressure and wear rate can vary by orders of magnitude during tests of common materials. A single average wear rate and a single wear mechanism cannot reflect such variations, and a better understanding of the wear test results can be developed by doing interrupted tests and examining the results in light of plausible simple models. Curve fitting programs that do not require programming can be useful tools to examine models give physically reasonable fits to the measured data. Here, the form of the functions were typical of processes that involve a sudden transition with pressure or temperature. Such an approach would need to be combined with surface characterization techniques to give any confidence as to the accuracy of such models.

Certainly more test results that measure the variation of wear scar as a function of time are desirable. Because the current analysis is semiempirical, more data analysis is required to ensure general applicability of the results.

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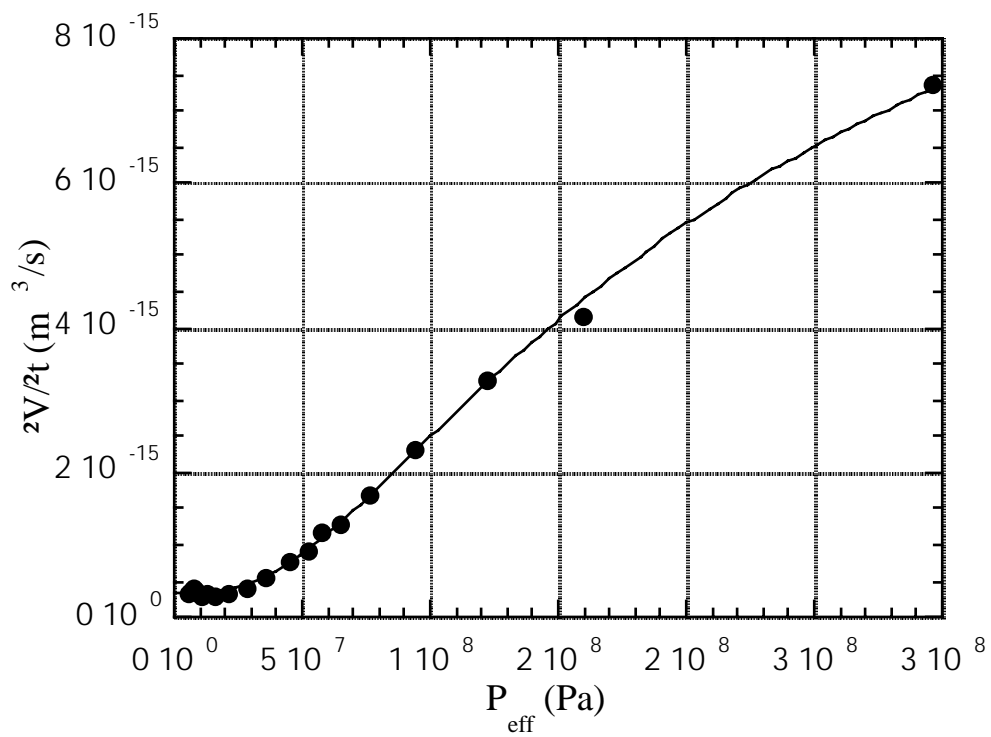


Fig. 1 $\frac{\Delta V}{\Delta t}$ plotted as a function of P_{eff} for Mecklenburg's data, and fitted curve.

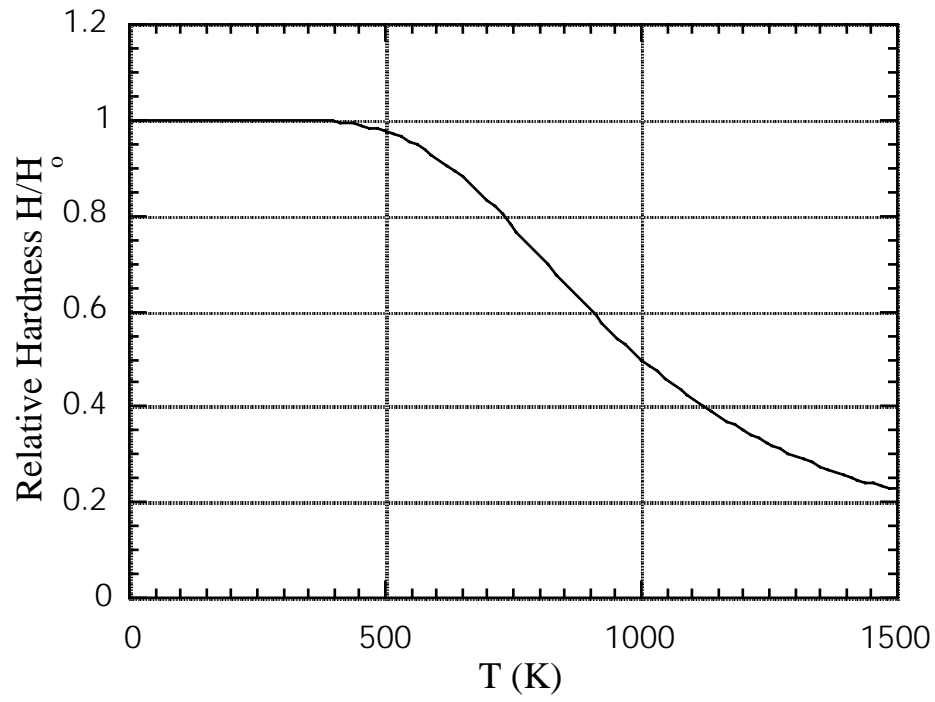


Fig. 2 Hardness curve that has been calculated from curve fitting of model to data in Fig. 1 to obtain parameters c and b .

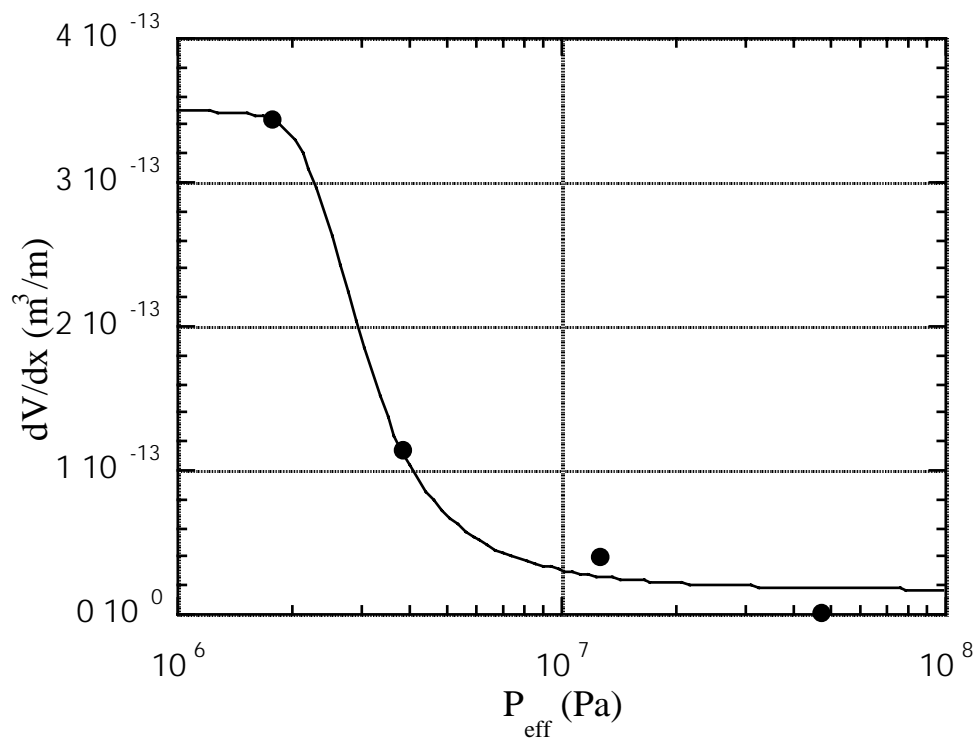


Fig. 3 $\frac{dV}{dx}$ as a function of P_{eff} for ZrO_2 sliding data

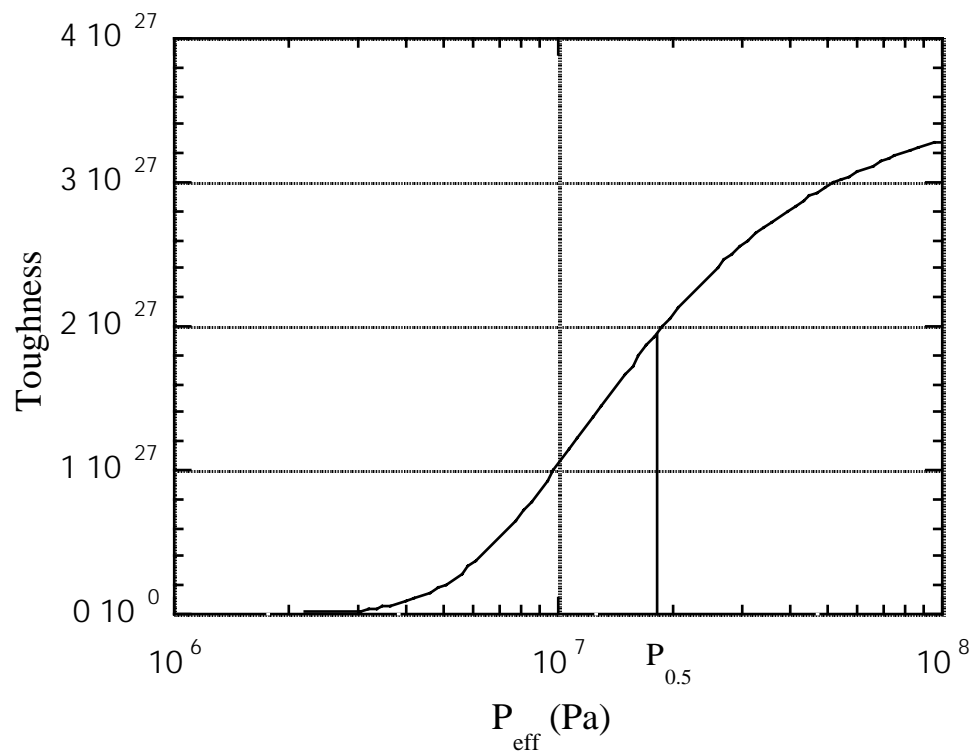


Fig. 4. Toughness curve that has been calculated from curve fitting of model to data in Fig. 3.